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Stormwater runoff to an impaired lake: impacts and solutions

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Abstract Stormwater runoff can represent a significant source of pollutants to downstream water bodies. An integrated assessment was conducted for the Spring Lake watershed in western Michigan because of concerns that increased impervious land cover in the watershed, especially in sub-basins adjacent to Spring Lake, would result in greater stormwater runoff and pollutant loads. Spring Lake has a history of high total phosphorus (TP) concentrations and cyanobacterial blooms. An alum treatment, paid for by an assessment, was applied to Spring Lake in 2005 to control internal phosphorus loading; hence, there was an economic incentive for stakeholders to limit new phosphorus from entering the lake, which otherwise would reduce the long-term efficacy of the alum treatment. This study provides a novel six-step process that identifies priority areas and optimally reduces nonpoint sources of pollution. We identified a suite of best management practices to be placed in the watershed, assessed their optimal locations based on pollutant sources, and modeled the degree to which their implementation would reduce TP and total suspended solids. Application of the modeled best management practices (BMPs) resulted in a 15 % reduction in TP load and a 17 % reduction in total suspended solid load. Reductions were not uniform throughout the watershed, with the greatest reductions closest to Spring Lake. We also developed a flow chart for BMP selection, which may be transferable to other watersheds with similar issues.

Keywords Stormwater · Integrated assessment · Best management practices · Spring Lake · Impervious surface · Water quality

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Introduction

The management of stormwater and stormwater runoff is an important issue for municipalities, whose citizenry demand clean drinking water, flood prevention, water drainage, and sanitation (Chocat et al. 2001). As new development throughout the USA continues to outpace population growth (Theobald 2005), there is a greater loss of rural and natural lands to increasing amounts of impervious cover, such as roadways, sidewalks, rooftops, driveways, and parking lots (Dougherty et al. 2006). This, in turn, results in greater volumes of stormwater runoff.

Stormwater runoff creates a variety of problems for land use managers, homeowners, fish and wildlife, and ecological systems. As more water flows into streams and rivers, it can result in unstable and eroding channels, loss of instream habitat, and more severe and more frequent flooding problems (Paul and Meyer 2001; Walsh et al. 2005). It also collects pollutants (such as street dust, eroded sediments, heavy metals, road salt, oil and grease, organic matter, nutrients, and pesticides) from impervious surfaces, farm fields, residential lawns, and commercial and industrial properties, and deposits

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them in receiving waterbodies (Domagalski 1996; Tsihrintzis and Hamid 1997; McFarland and Hauck 1999; Obropta and Kardos 2007). This, in turn, can degrade water quality, lead to fish kills and loss of species diversity, stimulate algae blooms, and create public health risks (Trim and Marcus 1990; Obropta and Kardos 2007; Johnson et al. 2011). Generally, there is a positive relationship between impervious surface cover within a watershed and environmental problems (Alberti et al. 2007), although there is debate in the literature as to how much impervious cover constitutes water quality impairment. Watersheds with impervious surface cover greater than 10 % are often considered to be impaired (Schueler 1994; Wang et al. 2001), but water quality impacts are measurable in watersheds with even lower levels of hardened surface areas (King et al. 2011).

Stormwater-related impacts are expected only to increase as climate change progresses (Madsen and Figdor 2007). Scientists are predicting that climate change will cause warming temperatures and an increase in the frequency of extremes in the hydrologic cycle—i.e., severe storms, increased flooding, and more periods of drought (Patz et al. 2008). Heavy runoff associated with these severe storm events can increase the risk of sewage overflows, contaminate local recreational waters, decrease the productivity of agricultural lands, and increase the risk of human illnesses (Madsen and Figdor 2007; McLellan et al. 2007; Patz et al. 2008). These problems can be further compounded by waterfront urbanization, which reduces flow path lengths and accelerates stormwater runoff into local waterways (Beighley et al. 2008).

Although numerous studies have been conducted addressing the water quality impacts of stormwater and its runoff, considerable obstacles continue to impede progress in developing and applying effective watershed-based approaches to managing stormwater. In many cases, local officials simply do not fully understand the impacts of, or the need to control, stormwater runoff. While they may be concerned about the quality of a natural resource, there may be no consensus about the goals for management of that resource. Alternatively, the value of the resource may not be considered high enough to spend money fixing the associated problems, and other budgetary items take priority. Decision-makers simply may be unaware of the impacts of stormwater discharges to their local water resources. Although flood control is an obvious problem that needs attention, the reduction in groundwater baseflow resulting from impervious surfaces that limits or prevents water from soaking into the ground is less noticeable. In addition, uncertainties in the performance and cost of stormwater control measures, limited funding and other resources, and ongoing maintenance and opportunity costs can impede implementation of stormwater best management practices (BMPs) (Roy et al. 2008). Finally, future problems resulting from stormwater runoff have not been fully identified in urbanizing watersheds.

This study is part of an integrated assessment to address stormwater issues in the Spring Lake watershed, located in west Michigan (Isely et al. 2014). Integrated assessment (IA) is the synthesis of existing natural and social scientific knowledge to solve a natural resource management problem or policy question (Parson 1995; Jakeman and Letcher 2003; Hillman et al. 2005; Scavia and Bricker 2006). IA is well-suited to address watershed management issues given the value that humans place on water resources, the complexities associated with its management, and increasing pressures being placed on this resource given changes in population, land use, and climate. While several studies have used IA to examine watershed-level questions (Croke et al. 2007; Parker et al. 2009), IA has been less frequently employed to address stormwater management, which also involves complex ecological, political, and social processes. In the current study, we explicitly addressed the policy and management objectives outlined by local municipalities as part of the IA process, which included the identification of the causes, as well as the consequences of, and potential solutions to, stormwater discharges in the Spring Lake watershed (Isely et al. 2014).

Methods

Site description

The Spring Lake watershed encompasses ~137 km^2 in Ottawa and Muskegon counties in Michigan and includes 11 municipalities; there are two communities downstream of Spring Lake along the Grand River toward its outlet at Lake Michigan (Fig. 1). The soils throughout the watershed are predominantly sand or sandy-textured, with more than 76 % of the soils classified under hydrologic soil groups A or B, which have high to highly moderate rainfall infiltration rates and

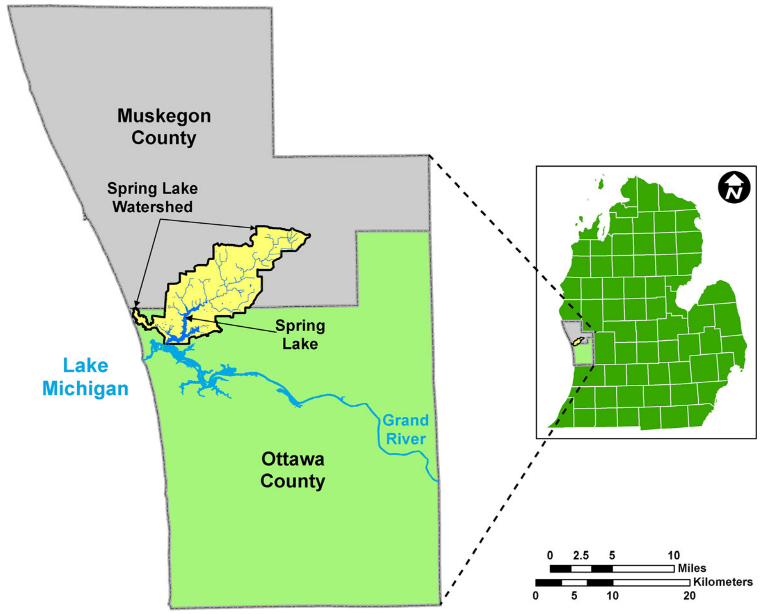

Fig. 1 *Inset*: location of the Spring Lake watershed in the west-central portion of Michigan's lower peninsula. *Blow-up*: Spring Lake watershed (*yellow*) location in Muskegon and Ottawa counties

low stormwater runoff potential. The average annual rainfall for the Spring Lake watershed is 92.6 cm. per year.

Spring Lake drains to the Grand River, at a point approximately 1 km east of Lake Michigan. It has a surface area of 5.25 km^2, with mean and maximum depths of 6 and 13 m, respectively. Prior to an alum application in 2005 to control internal phosphorus loading, surface water total phosphorus (TP) concentrations averaged ~92 μg/L during the summer; following the alum application, TP concentrations declined to ~25 μg/L (Steinman and Ogdahl 2008, 2012), although the lake still experiences periodic cyanobacterial blooms during the summer (Xie et al. 2012).

Integrated assessment process

IA is an active and rapidly developing field, and a multitude of approaches exist to aid in solving environmental resource management questions and policy issues (Hisschemöller et al. 2001). For our IA, we selected the approach outlined in Scavia and Bricker (2006). This adapted approach included five underlying steps that guided the Rein in the Runoff Integrated Assessment (Fig. 2). Each of these steps had several components, and each one was informed by a broad range of participants, including scientists (team members and project reviewers), decision-makers and stakeholders (project partners), and members of the general public (Rabalais et al. 2002). After we defined the relevant policy question (see below) around which the IA was to be performed (step 1), we documented the status and trends of appropriate environmental, social, and economic conditions related to the issue (step 2). This was followed by our describing the environmental, social, and economic causes and consequences of those trends (step 3) and providing forecasts of likely future conditions under a range of policy or management options (step 4). Finally, we provided technical guidance for the most cost-effective means of implementing each of those options, accompanied by an assessment of the uncertainties associated with the information generated in steps 1–5 (Fig. 2). Stakeholder education and input provided a critical feedback loop for the process (AWRI 2009; Isely et al. 2014).

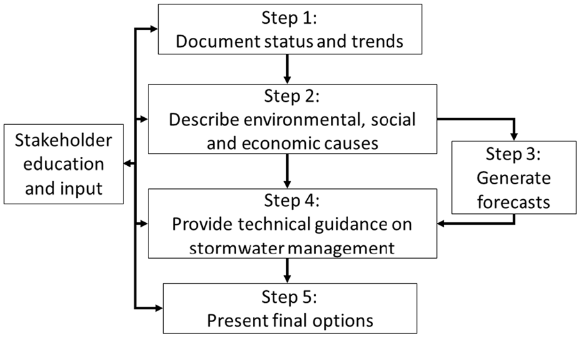

Fig. 2 Integrated assessment approach for stormwater management alternatives in the Spring Lake watershed

The initial policy question for this IA was developed by Michigan Sea Grant and public officials from Spring Lake Township and the Village of Spring Lake. The policy and management objectives that these communities had regarding water quality and the management of stormwater runoff included the identification of the causes, consequences, and correctives of stormwater discharges to the watersheds surrounding Spring Lake Township and the Village of Spring Lake, specifically Spring Lake, the Grand River, and ultimately Lake Michigan. However, once established, the project team—with input from these same community representatives—expanded the policy question to include the other communities within the Spring Lake watershed and the adjacent communities further downstream to the mouth of the Grand River at Lake Michigan to incorporate a broader group of stakeholders. The revised policy question for the Rein in the Runoff IA was as follows: "What stormwater management alternatives are available to the communities in the Spring Lake watershed that allow for future development and also mitigate the effects of stormwater discharges and improve the water quality in Spring Lake, the Grand River, and ultimately, Lake Michigan?"

To most effectively answer this policy question for local and regional stakeholders and accomplish the identified project goals, the project team adapted the Scavia and Bricker (2006) IA approach.

Land use change analysis

Land use change analysis used the 2006 National Agricultural Imagery Program (NAIP) digital orthophotograph (1–2-m pixel resolution) data in conjunction with existing 1992/1997 land use and land cover vector polygon dataset within the ESRI™ ArcView GIS 3.3 program. The Spring Lake watershed boundary was clipped from the 2006 data to create an updated GIS layer through photographic interpretation using the Michigan Land Cover/Use Classification System. Land use and land cover data were verified through field QA/QC reconnaissance, based on ~10 % of the vector polygons throughout the project area. We estimated that 95 % of the landscape surface of the Spring Lake watershed is accurately represented in the 2006 land use and land cover update. Accurate land use/cover data were critical given their influence in subsequent pollutant modeling, the identification of percent impervious surface cover, and the siting of potential stormwater management BMPs within the watershed. Fifteen land use/cover classifications were identified for the land use change analysis (cf. Table 1).

Impervious Surface Analysis Tool

The Impervious Surface Analysis Tool (ISAT) was developed by the NOAA Coastal Services Center to determine the total percentage of impervious surface area within a specific landscape. ISAT applies impervious surface coefficients to land use and land cover data to determine the total and the percentage of impervious surface area within specified vector polygons. We used ISAT with ArcGIS 9.4 to determine the percent of impervious surface cover for the Spring Lake watershed over time, applying it to the land use and land cover data for each sub-watershed basin in 1978, 1992–1997, and 2006.

Pollutant load modeling

Pollutant Loading Application (PLOAD) is a simplified GIS-based model that estimates user-specified nonpoint sources of pollution to a watershed on an annual average basis (Baker et al. 2014). We selected PLOAD (as opposed to SWAT, for example) because PLOAD is a

Table 1 Event mean concentrations (EMCs) for total phosphorus and total suspended solids for the 15 land use/land cover classifications identified in the Spring Lake watershed

Land use/land cover	Total P (mg/L)	TSS (mg/L)
Bare/sparsely vegetated	0.08	30
Commercial/industrial/transportation	0.34	35
Coniferous forest	0.15	14
Cropland and pasture	0.4	27
Deciduous forest	0.15	16
Emergent herbaceous wetlands	0.11	8
Herbaceous open land/grasslands	0.15	19
Mixed forest	0.15	15
Orchards/vineyards/other	0.37	17
Other agricultural land	0.39	25
Residential	0.5	25
Shrub/low-density trees	0.15	22
Urban/recreational grasses	0.37	20
Water	0.08	3
Woody wetlands	0.11	8

simplified and generic GIS-based modeling tool that was specifically recommended by the US EPA to estimate nonpoint pollutant loads on an annual average basis for NPDES stormwater permitting and watershed management. PLOAD can be run under two different modeling approaches: the US EPA's simple method or the export coefficient method. Both require a very limited number of readily available geo-spatial and tabular data for input; in contrast, SWAT is a much more comprehensive and sophisticated model but requires a large number of input parameters, necessitating supplemental calibration and validation procedures, which were beyond the scope and time available for this project (cf. Nejadhashemi et al. 2011; Arnold et al. 2012).

We used US EPA's simple method, which is an empirical approach for estimating nonpoint source pollutant loads from urban development sites in watersheds smaller than 1 mi^2 (US EPA 2001; Goodwin 2007). Although the Spring Lake watershed is larger than this threshold, the alternative method (export coefficient) was found deficient because it does not take into account precipitation or impervious surface area (US EPA 2001), and the loading rate is derived from export coefficient tables, which were not available for Michigan or other regions similar to the Spring Lake watershed. In addition, the PLOAD simple method has been successfully applied in watershed basins even larger than Spring Lake (Syed and Jodoin 2006; Goodwin 2007). We adopted the approach used by Syed and Jodoin (2006), who applied the PLOAD simple method to sub-basins in the Lake St. Clair (MI) drainage area; both watersheds are located in Michigan's lower peninsula with similar degrees of latitude, landscapes, lithologies (glacial modification of regolith), and land use/cover types.

We divided the Spring Lake watershed into 26 sub-basins, ranging in area from 0.05 to 5.31 mi^2 using ArcSWAT (Soil and Water Assessment Tool for ArcGIS). Estimates for total phosphorus (TP) and total suspended solid (TSS) loads to Spring Lake were calculated for each of the 26 sub-basins within the Spring Lake watershed by creating a BASINS project file for each of the land use and land cover GIS data layers (1978, 1992–1997, and 2006) and then running each layer separately through the BASINS PLOAD modeling interface. We also calculated a rainfall to runoff ratio for the sub-basins based on the long-term precipitation data (1899–2007) for the watershed. PLOAD does not use hydrologic soil group data within the model to adjust for rainfall-runoff; curve numbers were derived from existing hydrologic soil group and land use/cover data to determine a rainfall-runoff coefficient for each sub-basin. Utilizing these curve numbers with the long-term precipitation data gave more accurate rainfall-runoff data per sub-basin than using the same average yearly rainfall value for the entire watershed, with no regard to the reduction of runoff because of storage and initial abstraction (i.e., interception, infiltration, depression storage, and antecedent soil moisture) (Syed and Jodoin 2006).

Best management practices

Stormwater runoff is generally controlled through the implementation of BMPs. BMPs are stormwater control measures that slow, retain, or absorb nonpoint source pollutants associated with runoff (Tsihrintzis and Hamid 1997; Chang et al. 2007). However, in the USA, the term "BMP" has come to mean any stormwater control measure and not just the "best" ones (Roy et al. 2008).

The BMP selection analysis followed the methodology proposed by Schueler et al. (2007). The BMP selection approach focused on macro-scale areas within the Spring Lake watershed that would be suitable for the implementation of different types of BMPs: infiltration BMPs (such as infiltration swales and basins, rain gardens, porous pavement, and dry wells), filtration BMPs (such as vegetation or subsurface layers of soil, sand, or aggregate), regional storage areas, regional treatment areas, and site-specific BMPs on publicly held lands. We followed a six-step process to identify opportunities for the implementation of different structural and non-structural stormwater BMPs.

Step 1: Identification of priority areas

The PLOAD model results, aerial photographs, and existing land uses and land covers were compared to identify priority implementation areas for stormwater BMPs. We focused on areas with higher phosphorus loadings (based on PLOAD results) and land use/cover types generally associated with higher nutrient loadings, such as impervious surfaces and agricultural lands. We also considered proximity to water bodies because the closer the source of stormwater pollution is to these water bodies, the less opportunity there is for natural processes to reduce nutrient levels (Groffman et al. 2003).

Step 2: Evaluation of existing riparian buffers

Aerial photography was used to identify which streams or portions of streams currently lack a forested riparian buffer; those areas were identified as BMP opportunities. We also prioritized native vegetative buffers along the lakeshore; a native grass buffer would provide filtering of stormwater runoff from adjacent lawns and impervious surfaces prior to discharge to the lake (Zhang et al. 2010).

Step 3: Identification of public properties for BMPs

Public maintenance yards and areas where soils and minerals are stored aboveground were given higher priority based on the level of nutrients discharged within runoff from these types of sites. Depending on soil types, filtrative or infiltrative BMPs can be installed on these public sites.

Step: 4: Identification of opportunities for infiltration BMPs

Hydrologic soil groups A and B, generally considered good for infiltration, were identified as an attribute of the maps used in BMP selection.

Step 5: Identification of opportunities for filtration BMPs

Where existing soils do not have high rates of permeability, filtrative BMPs can be used. While infiltrative BMPs will often provide a higher benefit to cost ratio than filtrative BMPs, filtrative BMPs are still appropriate in certain areas. They are particularly applicable in sites that are in close proximity or immediately adjacent to a waterbody or in areas where soil and other conditions are not favorable for infiltration, such as contaminated sites or sites with proposed future uses that are incompatible with infiltration.

Step 6: Identification of "universal" BMPs

So named because they can be applied universally, some BMPs are appropriate "retrofits" to existing development, including structural BMPS, such as riparian buffers or planting native vegetation, as well as non-structural BMPs like rain barrels/cisterns, the disconnection of roof leads, or the enactment of fertilizer ordinances.

Following the BMP analysis, we applied the structural BMPs to the high-priority areas by converting the existing land use/cover data layer to new classifications (Table 2). The residential infiltration, regional treatment, and site-specific BMP areas were reclassified as urban/recreational grasses. The regional storage areas were reclassified as emergent herbaceous wetlands. Finally, filtration BMP areas were reclassified as woody wetlands (Table 2). We then qualitatively identified optimal locations for the BMPs based on location in the watershed (priority given to locations closer to water bodies) and performance characteristics (e.g., infiltration BMPs in locations with highly permeable soil types). We ran PLOAD on the 2006 land use and land cover GIS layer to show the changes in nutrient loadings to Spring Lake after the application of these various BMPs throughout the watershed. Additional detail on the land use change analysis, ISAT, PLOAD, and BMP selection process is provided in AWRI (2009).

Results

Land use/land cover

Between 1978 and 2006, forest cover (deciduous, coniferous, and mixed) remained the biggest land use class at 41 % but declined by a modest 8.6 % from 6133 to 5599 ha (Fig. 3). In contrast, residential and urban

Table 2 Length and size of the structural BMPs and corresponding land use/land cover classifications used in PLOAD model runs

Structural BMPs	Length/size	Land use/land cover classification	Length/size
Infiltration swales	97.8 km	Grasslands	97.8 km
Riparian buffers	30.6 km	Mixed forest	30.6 km
Filtration BMP areas	57.1 km	Woody wetlands	57.1 ha
Regional storage areas	3.2 ha	Emergent herbaceous wetlands	3.2 ha
Regional treatment areas	130 ha	Urban/recreational grasses	1061 ha
Site-specific BMPs	186.3 ha	Urban/recreational grasses	1061 ha
Residential infiltration areas	745 ha	Urban/recreational grasses	1061 ha

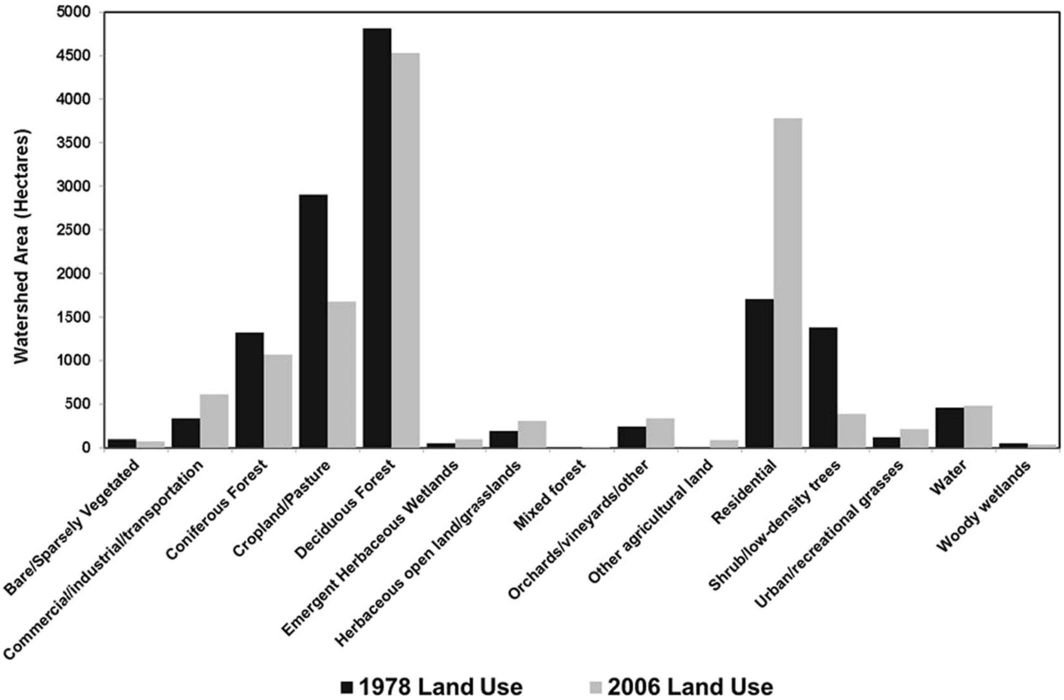

Fig. 3 Land use change in the Spring Lake watershed 1978–2006

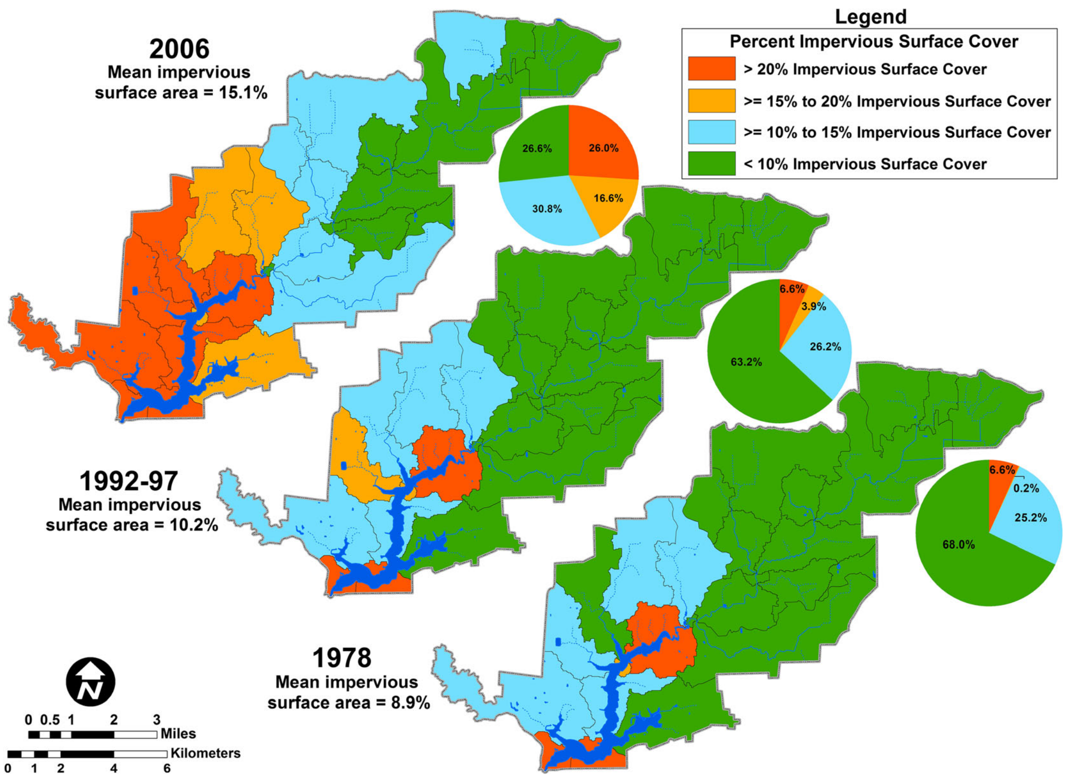

Fig. 4 Impervious surface area in the Spring Lake watershed in 1978 (*bottom*), 1992–1997 (*middle*), and 2006 (*top*). Associated pie charts show percent impervious surface distribution within the watershed for each time period

(commercial/industrial/transportation) land uses increased by more than 120 % (from 1708 to 3781 ha) and 79 % (from 339 to 609 ha), respectively, during that 28-year period, largely at the expense of the collective agricultural land covers, which declined 42 %, from 2904 to 1675 ha (Fig. 3).

Urban and exurban growth in the Spring Lake watershed has resulted in an increase in total impervious area, particularly in the communities adjacent to Spring Lake (Fig. 4). Between 1992–1997 and 2006, overall watershed mean percent impervious surface area increased from 8.9 to 15.1 %. In addition, watershed area with limited impervious surface areas (i.e., <10 %) decreased from 68 % in 1978 to only 27 % in 2006 (Fig. 4). In contrast, areas with impervious surface areas >20 % increased from 6.6 % in both 1978 and 1992–1997 to 26 % in 2006 (Fig. 4). Significantly, the increase in impervious cover was distributed in a very nonuniform fashion through the watershed, with the greatest amount of impervious cover immediately adjacent to Spring Lake (Fig. 4).

Pollutant load modeling

Both TP and TSS loads increased by ~9 % between 1978 and 1992/1997 (Fig. 5). Between 1992/1997 and 2006, TP increased an additional 46 % from 3.96 to 5.76 metric tons/year, while TSS increased an additional 36 % from 272.20 to 371.17 metric tons/year (Fig. 5).

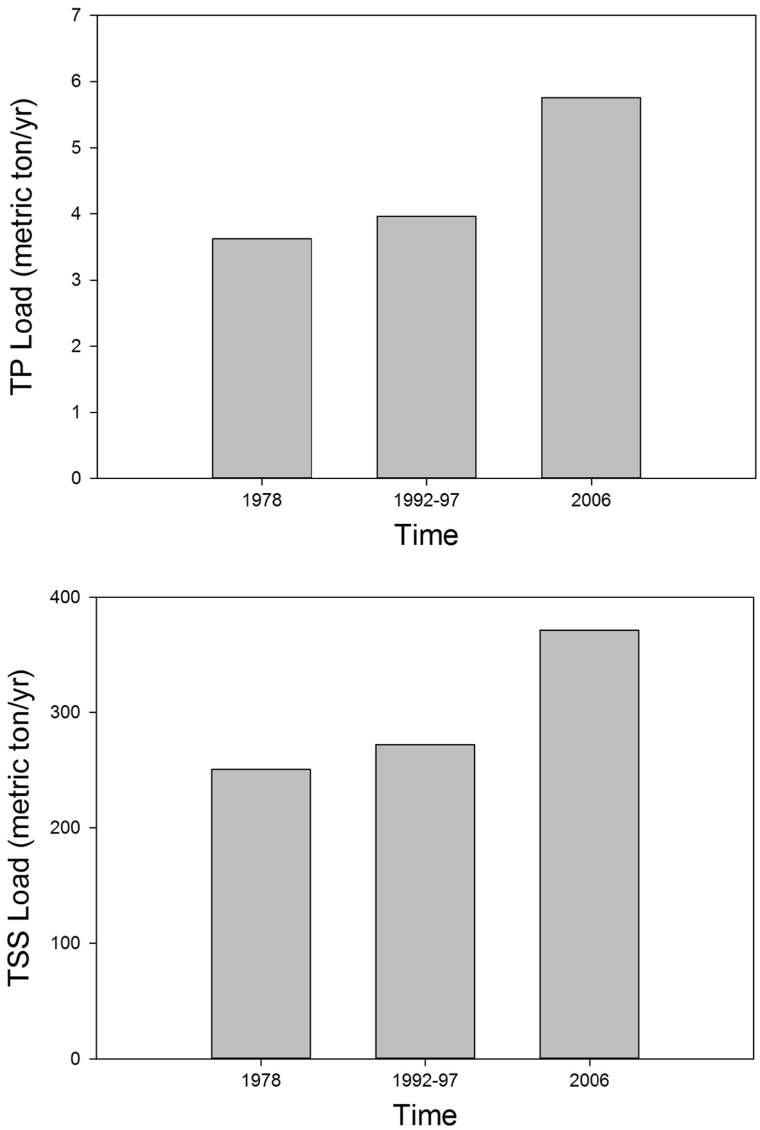

Fig. 5 Total phosphorus and total suspended solid loads (metric tons/year) from the Spring Lake watershed for 1978, 1992–1997, and 2006 based on PLOAD model results

These increases were consistent with the increases in residential and urban land use classes adjacent to Spring Lake, which came at the expense of natural vegetation and cropland/pasture land use and cover types (Fig. 3). The land use/cover type with the highest event mean concentration for TP was residential, whereas the highest event mean concentration for TSS was associated with urban land use/cover (Table 1). Both of these land uses are distributed disproportionately close to or adjacent to Spring Lake (cf. Fig. 9); this increase in land use/cover types with limited infiltration capacity close to the lake, combined with high TP and TSS concentrations during stormwater runoff, results in Spring Lake becoming particularly vulnerable to water quality impairments.

Best management practices

The application of modeled BMPs to the 2006 land use and land cover data layer resulted in a 15 % decline in TP, from 5.8 to 4.9 metric tons/year. TSS loads were reduced by 17 % with the implementation of modeled BMPs, from 371.2 to 309.4 metric tons/year. The reductions were not uniform throughout the watershed, with minimal or no load reductions in the sub-basins of the upper watershed (Figs. 6 and 7). The areas with the most substantial reductions were located adjacent to Spring Lake, with the exception of the small sub-basin at the southwest corner of the watershed, which is the location of Spring Lake Village (Figs. 6 and 7). Given the dense urban development in the village, available area for BMP implementation was extremely limited, and hence load reductions were negligible.

Discussion

Changing land use associated with urbanization often results in increases in nutrient loads to aquatic systems, which in turn can lead to impaired water quality, including hypoxia, harmful algal blooms, fish kills, loss of biodiversity, and increases in nuisance species (Smith et al. 1999; Paul and Meyer 2001; Kaushal et al. 2008; Catherine et al. 2013; Milstead et al. 2013). Indeed, excess nutrients are a primary cause of lake water quality impairments throughout the USA (US EPA 2002).

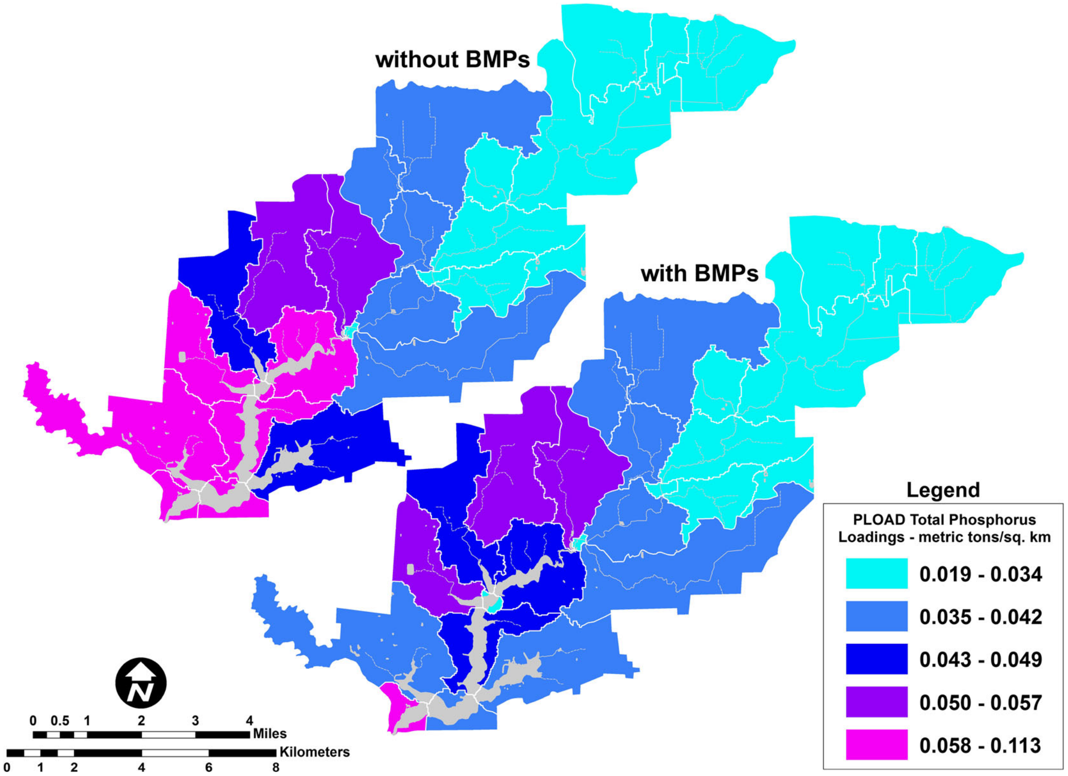

Fig. 6 Total phosphorus loads for each sub-basin in the Spring Lake watershed with BMPs in place (*bottom*) and without BMPs (*top*) based on PLOAD model results

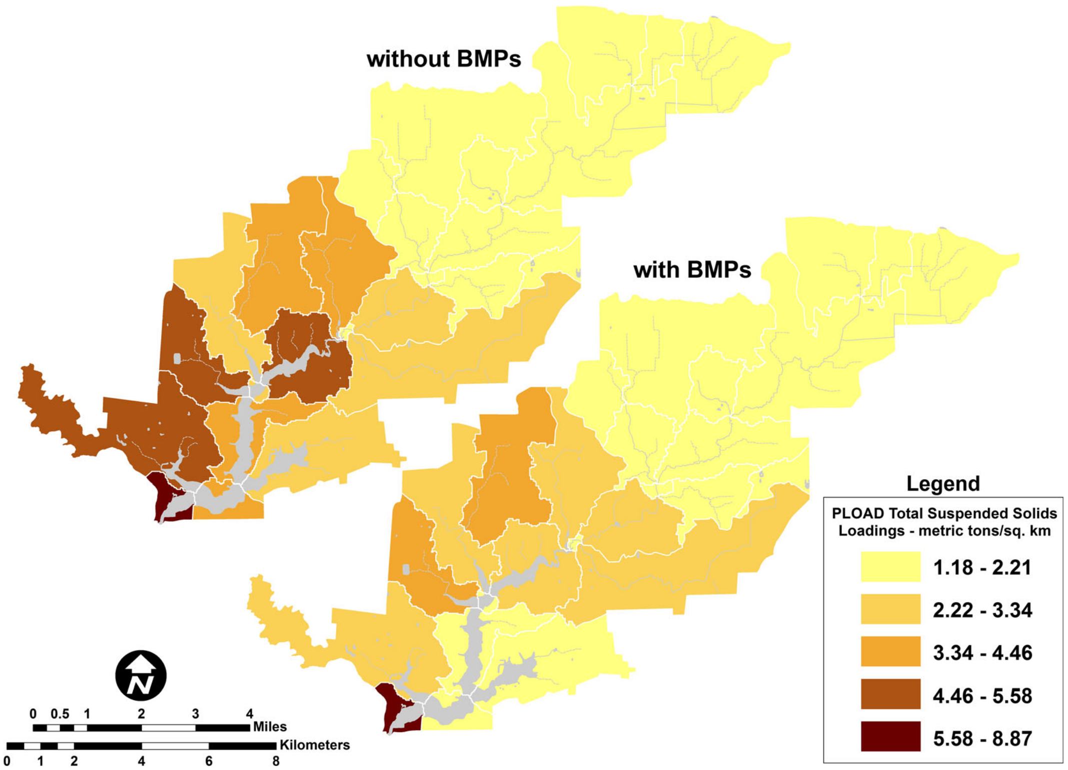

Fig. 7 Total suspended solid loads for each sub-basin in the Spring Lake watershed with BMPs in place (*bottom*) and without BMPs (*top*) based on PLOAD model results

Nonpoint sources of pollution, especially stormwater runoff, are notoriously difficult to manage given their diffuse nature. Best management practices are most often recommended to control these inputs, and despite their cost-effectiveness when ecosystem services are also considered (Talberth et al. 2013), their up-front costs can be problematic for local municipalities, especially when compounded by maintenance costs. In addition, the degree to which they reduce pollutant loading varies depending on the pollutant in question, their location, and BMP design (Rosenquist et al. 2010). Hence, the problem of stormwater runoff involves more than technical solutions—social and economic dynamics also must be addressed (van Kerkhoff and Lebel 2006; Isely et al. 2014).

We developed a flow chart that outlines the BMP selection approach we used in the Spring Lake watershed (Fig. 8). This approach could be adapted for use in other watersheds, as well. At the first level, BMPs are separated into those that can be applied anywhere in the watershed (universal), such as modified ordinances to address stormwater and education/outreach activities vs. those targeted for high-priority areas, including riparian properties, public lands, and identified high-P-source land use/land cover areas (e.g., agriculture, impervious, residential; Fig. 8). BMPs for these high-P areas are further subdivided into those regions with permeable vs. impermeable soils (Fig. 8). Based on our six-step approach (see "Methods"), we identified locations in the watershed for BMP implementation (Fig. 8). Riparian buffer strips and infiltration swales predominate in the upper watershed, whereas filtration BMPs, site-specific BMPs on public property, and residential infiltration areas are more common closer to Spring Lake (Fig. 9). This is an idealized approach, as actual implementation will depend on funding, site availability, and local ordinances (Isely et al. 2014). However, it did allow us to model the cumulative impact of BMPs on load reductions in the watershed.

The control of stormwater runoff pollution has particular significance for Spring Lake given the financial investments already made in lake management. In 2005, an ~$900,000 alum treatment was applied to Spring Lake to inactivate internal phosphorus loading and to control cyanobacterial blooms (Steinman and Ogdahl 2008, 2012); this cost was

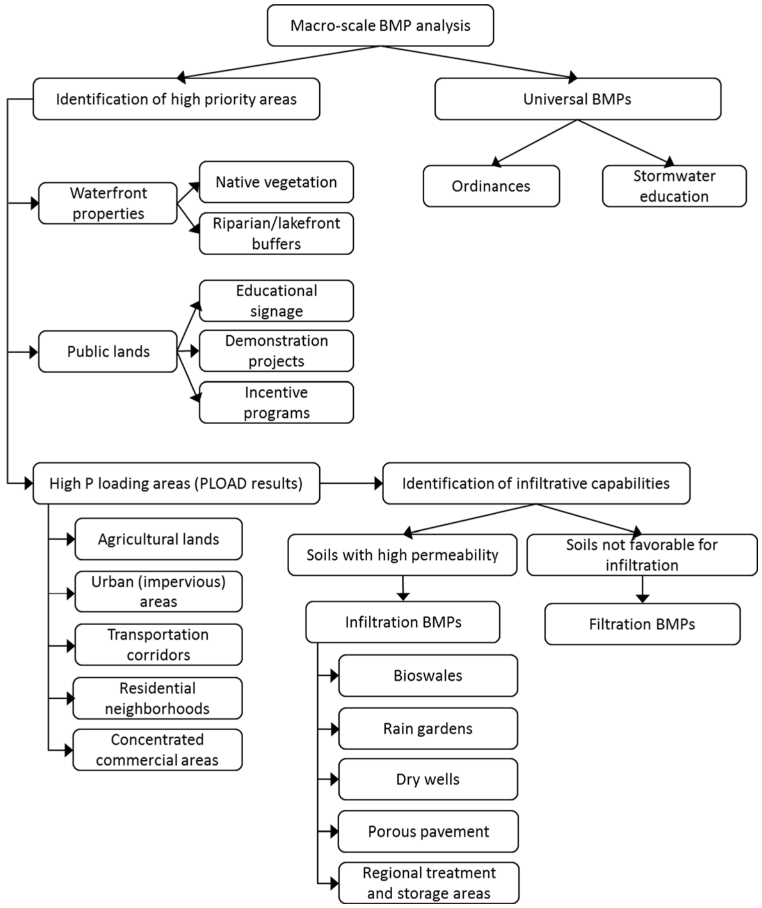

Fig. 8 Flow chart showing the BMP selection process for the Spring Lake watershed

borne by the residents. The effectiveness of the alum treatment is contingent on controlling new sources of phosphorus to the lake (Kennedy and Cooke 1982), so continued input of stormwater runoff will both negate the benefit of the alum treatment and reduce the value of the residential investment.

These modeling results provide a framework from which management actions can be constructed. While there is inherent uncertainty in the use of models to forecast environmental impacts (Refsgaard et al. 2007), they can be used to help illustrate the relative utility of BMPs and how load reduction is influenced by site location. Based on a desired or regulated load reduction, as well as available funding, the BMP footprint can be expanded (or retracted) to meet management needs. Ultimately, a collaborative approach that integrates scientific, social, economic, and political forces is necessary to tackle the issues surrounding stormwater runoff (Isely et al. 2014).

Conclusions

Population growth in rapidly developing areas is resulting in more hardened—and less natural—surfaces. In many watersheds, including Spring Lake, this development is skewed to areas closest to the receiving water body. These impervious areas have changed the natural hydrology of the watershed. Instead of rainwater and snowmelt soaking into the sandy soils, they now run off these impervious areas potentially impacting water quality, real estate value (Dodds et al. 2008), and quality of life. The application of alum in 2005 to Spring Lake decreased the loading (or release) of phosphorus from the sediments in Spring Lake but has done nothing to stop new nutrient inputs from entering the lake from the land. If growth and development continue to occur and no additional actions are taken to control and manage stormwater runoff, the nutrient loads to Spring Lake and its adjoining waterways will only increase. Based on

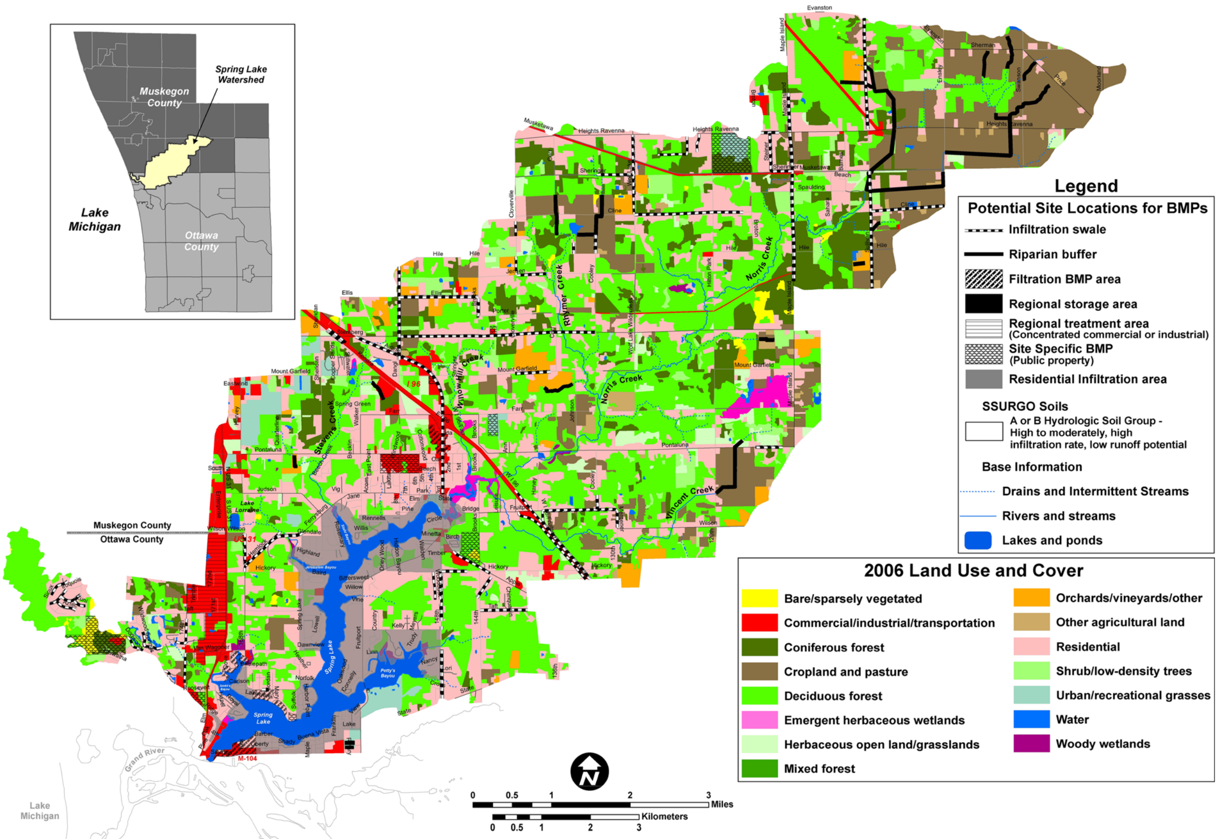

Fig. 9 Potential location of BMPs, based on high-priority-area analysis, in the Spring Lake watershed

technical analyses and stakeholder input, stormwater management priorities for the Spring Lake watershed were generated and prioritized, including the restoration of riparian and littoral buffers and implementation of BMPs in the areas that contribute the highest pollutant loads to Spring Lake. Using this IA approach, community leaders, elected officials, and the general public now have a defensible framework on which to base action. While additional site-specific analyses may be necessary to better quantify the effects of different combinations of BMPs and low-impact development strategies, the overall strategy remains unchanged.

One of the primary challenges in the completion of our IA was the limited amount of feedback from stakeholders on the more technical aspects of local stormwater management goals and potential solutions. The issues associated with stormwater are complex and sometimes difficult for members of the general public to grasp (Isely et al. 2014). Although a small group of stakeholders was involved in several aspects of the IA, overall stakeholder input was limited. This suggests a greater need for ongoing stakeholder education regarding stormwater runoff (cf. Roy et al. 2008).

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Conflict of interest The authors declare that they have no competing interests.

References

Alberti, M., Booth, D., Hill, K., Coburn, B., Avolio, C., Coe, S., & Spirandelli, D. (2007). The impact of urban patterns on aquatic ecosystems: an empirical analysis in Puget lowland sub-basins. *Landscape and Urban Planning*, *80*, 345–361.

Annis water resources institute (AWRI). (2009). Rein in the Runoff: alternative stormwater management practices that address the environmental, social, and economic aspects of water resources in the Spring Lake Watershed (MI). Online URL: http://www.gvsu.edu/wri/director/rein-in-the-runoff-stormwater-integrated-assessment-in-28.htm (accessed February 6, 2015).

Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., Santhi, C., Harmel, R. D., van Griensven, A., Van Liew, M. W., Kannan, N., & Jha, M. K. (2012). SWAT: model use, calibration, and validation. *Transactions of the American Society of Agricultural and Biological Engineers*, *55*, 1491–1508.

Baker, R.J., Wieben, C.M., Lathrop, R.G., & Nicholson, R. S. (2014). Concentrations, loads, and yields of total nitrogen and total phosphorus in the Barnegat Bay-Little Egg Harbor Watershed, New Jersey, 1989–2011, at multiple spatial scales; U.S. Geological Survey Scientific Investigations Report 2014–5072, 64 p.

Beighley, R. E., Dunne, T., & Melack, J. M. (2008). Impacts of climate variability and land use alterations on frequency distributions of terrestrial runoff loading to coastal waters in Southern California. *Journal of the American Water Resources Association*, *44*, 62–74.

Catherine, A., Mouillot, D., Maloufi, S., Troussellier, M., & Bernard, C. (2013). Projecting the impact of regional land-use change and water management policies on lake water quality: an application to periurban lakes and reservoirs. *PloS One, 8*, e72227.

Chang, C. L., Chiueh, P. T., & Lo, S. L. (2007). Effect of spatial variability of storm on the optimal placement of best management practices (BMPs). *Environmental Monitoring and Assessment*, *135*, 383–389.

Chocat, B., Krebs, P., Marsalek, J., Rauch, W., & Schilling, W. (2001). Urban drainage redefined: from stormwater removal to integrated management. *Water Science and Technology*, *43*, 61–68.

Croke, B. F. W., Ticehurst, J. L., Letcher, R. A., Norton, J. P., Newham, L. T. H., & Jakeman, A. J. (2007). Integrated assessment of water resources: Australian experiences. *Water Resources Management*, *21*, 351–373.

Dodds, W. K., Bouska, W. W., Eitzmann, J. L., Pilger, T. J., Pitts, K. L., Riley, A. J., Schloeser, J. T., & Thornbrugh, D. J. (2008). Eutrophication of US freshwaters: analysis of potential economic damages. *Environmental Science & Technology*, *43*, 12–19.

Domagalski, J. (1996). Pesticides and pesticide degradation products in stormwater runoff: Sacramento River basin, California. *Water Resources Bulletin*, *32*, 953–964.

Dougherty, M., Dymond, R. L., Grizzard Jr., T. J., Godrej, A. N., Zipper, C. E., Randolph, J., & Anderson-Cook, C. M. (2006). Empirical modeling of hydrologic and NPS pollutant flux in an urbanizing basin. *Journal of the American Water Resources Association*, *42*, 1408–1419.

Goodwin, K. (2007). *Total maximum daily load for biota for the River Rouge Watershed, including Bishop and Tonquish Creeks Washtenaw*. Michigan Department of Environmental Quality, Water Bureau Report, August:Wayne and Oakland counties.

Groffman, P. M., Bain, D. J., Band, L. E., Belt, K. T., Brush, G. S., Grove, J. M., Pouyat, R. V., Yesilonis, I. C., & Zipperer, W. C. (2003). Down by the riverside: urban riparian ecology. *Frontiers in Ecology and the Environment*, *1*, 315–321.

Hillman, T., Crase, L., Furze, B., Ananda, J., & Maybery, D. (2005). Multidisciplinary approaches to natural resource management. *Hydrobiologia*, *552*, 99–108.

Hisschemöller, M., Tol, R. S. J., & Vellinga, P. (2001). The relevance of participatory approaches to integrated environmental assessment. *Integrated Assessment*, *2*, 57–72.

Isely, E.S., Steinman, A.D., Isely, P.N., & Parsell, M.A. (2014). Building partnerships to address conservation and management of western Michigan's natural resources. *Freshwater Science, 33*, 679–685.

Jakeman, A. J., & Letcher, R. A. (2003). Integrated assessment and modelling: features, principles and examples for catchment management. *Environmental Modelling & Software*, *18*, 491–501.

Johnson, K., Steinman, A. D., Keiper, W. D., & Ruetz III, C. R. (2011). Biotic responses to low concentration urban road runoff. *Journal of the North American Benthological Society*, *30*, 710–727.

Kaushal, S. S., Groffman, P. M., Band, L. E., Shields, C. A., Morgan, R. P., Palmer, M. A., Belt, K. T., Swan, C. M., Findlay, S. E. G., & Fisher, G. T. (2008). Interaction between urbanization and climate variability amplifies watershed nitrate export in Maryland. *Environmental Science & Technology*, *42*, 5872–5878.

Kennedy, R. H., & Cooke, G. D. (1982). Control of lake phosphorus with aluminum sulfate: dose determination and application techniques. *Journal of the American Water Resources Association*, *18*, 389–395.

King, R. S., Baker, M. E., Kazyak, P. F., & Weller, D. E. (2011). How novel is too novel? Stream community thresholds at exceptionally low levels of catchment urbanization. *Ecological Applications*, *21*, 1659–1678.

Madsen, T., & Figdor, E. (2007). When it rains, it pours: global warming and the rising frequency of extreme precipitation in the United States. Report to Environment Michigan Research & Policy Center. Online URL: http://www.environmentmichigan.org/reports/mie/when-it-rains-it-pours-0 (accessed March 26, 2014).

McFarland, A. M. S., & Hauck, L. M. (1999). Relating agricultural land uses to in-stream stormwater quality. *Journal of Environmental Quality*, *28*, 836–844.

McLellan, S. L., Hollis, E. J., Depas, M. M., VanDyke, M., Harris, J., & Scopel, C. O. (2007). Distribution and fate of Escherichia coli in Lake Michigan following contamination with urban stormwater and combined sewer overflows. *Journal of Great Lakes Research*, *33*, 566–580.

Milstead, W.B., Hollister, J.W., Moore, R.B., & Walker, H.A. (2013). Estimating summer nutrient concentrations in northeastern lakes from SPARROW load predictions and modeled lake depth and volume. *PloS One, 8*, e81457.

Nejadhashemi, A.P., Woznicki, S.A., & Douglas-Mankin, K.R. (2011). Comparison of four models (STEPL, PLOAD, L-THIA, and SWAT) in simulating sediment, nitrogen, and phosphorus loads and pollutant source areas. *Transactions of the American Society of Agricultural and Biological Engineers, 54*, 875–890.

Obropta, C. C., & Kardos, J. S. (2007). Review of urban stormwater quality models: deterministic, stochastic, and hybrid approaches. *Journal of the American Water Resources Association*, *43*, 1508–1523.

Parker, J. S., R. Moore, & M. Weaver (2009). Developing participatory models of watershed management in the Sugar Creek Watershed (Ohio, USA). *Water Alternatives, 2*, 82–100.

Parson, E. A. (1995). Integrated assessment and environmental policy-making. *Energy Policy*, *23*, 463–475.

Patz, J.A., Vavrus, S.J., Uejio, C.K., & McLellan.S.L. (2008). Climate change and waterborne disease risk in the Great Lakes region of the U.S. *American Journal of Preventative Medicine, 35*, 451–458.

Paul, M. J., & Meyer, J. L. (2001). Streams in the urban landscape. *Annual Review of Ecology and Systematics*, *32*, 333–365.

Rabalais, N. N., Turner, R. E., & Scavia, D. (2002). Beyond science into policy: Gulf of Mexico hypoxia and the Mississippi River nutrient policy development for the Mississippi River watershed reflects the accumulated scientific evidence that the increase in nitrogen loading is the primary factor in the worsening of hypoxia in the northern Gulf of Mexico. *Bioscience*, *52*, 129–142.

Refsgaard, J. C., van der Sluijs, J. P., Højberg, A. L., & Vanrolleghem, P. A. (2007). Uncertainty in the environmental modelling process—a framework and guidance. *Environmental Modelling & Software*, *22*, 1543–1556.

Rosenquist, S. E., Hession, W. C., Eick, M. J., & Vaughan, D. H. (2010). Variability in adsorptive phosphorus removal by structural stormwater best management practices. *Ecological Engineering*, *36*, 664–671.

Roy, A. H., Wenger, S. J., Fletcher, T. D., Walsh, C. J., Ladson, A. R., Shuster, W. D., Thurston, H. W., & Brown, R. R. (2008). Impediments and solutions to sustainable, watershed-scale urban stormwater management: lessons from Australia and the United States. *Environmental Management*, *42*, 344–359.

Scavia, D., & Bricker, S. B. (2006). Coastal eutrophication assessment in the United States. *Biogeochemistry*, *79*, 187–208.

Schueler, T.R. (1994). The importance of imperviousness. *Watershed Protection Techniques, 1*, 100–111.

Schueler, T., Hirschman, D., Novotney, M. & Zielinski, J. (2007). Urban subwatershed restoration manual no. 3: urban stormwater retrofit practices (version 1). Center for Watershed Protection, http://www.cwp.org/Store/usrm/htm.

Smith V.H., Tilman, G.D., & Nekola, J.C. (1999). Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. *Environmental Pollution, 100*, 179–196. doi:10.1016/S0269-7491(99)00091–3.

Steinman, A. D., & Ogdahl, M. (2008). Ecological effects following an alum treatment in Spring Lake, Michigan. *Journal of Environmental Quality*, *37*, 22–29.

Steinman, A. D., & Ogdahl, M. (2012). Macroinvertebrate response and internal phosphorus loading in a Michigan Lake following alum treatment. *Journal of Environmental Quality*, *41*, 1540–1548.

Syed, A.U., & Jodoin, R.S. (2006). Estimation of nonpoint-source loads to total nitrogen, total phosphorus, and total suspended solids in the Black, Belle, and Pine River basins, Michigan, by use of the PLOAD model. U.S. Geological Survey, Scientific Investigations Report 2006–5071.

Talberth, J. G., Yonavjak, E., & Gartner, L. T. (2013). Green versus gray: nature's solutions to infrastructure demands. *Solutions*, *4*(1).

Theobald, D. M. (2005). Landscape patterns of exurban growth in the USA from 1980 to 2020. *Ecology & Society*, *10*, 32.

Trim, A. H., & Marcus, J. M. (1990). Integration of long-term fish kill data with ambient water quality monitoring data and application to water quality management. *Environmental Management*, *14*, 389–396.

Tsihrintzis, V. A., & Hamid, R. (1997). Modeling and management of urban stormwater runoff quality: a review. *Water Resources Management*, *11*, 137–164.

U.S. Environmental Protection Agency (2001). PLOAD version 3.0: an ArcView GIS tool to calculate nonpoint sources of pollution in watershed and stormwater projects. User's Manual, January.

U.S. Environmental Protection Agency (2002). National water quality inventory: report to Congress 2002 reporting cycle. Washington, D.C.. Available: Available online at: http://water.epa.gov/lawsregs/guidance/cwa/305b/2002report_index.cfm. Accessed 2013 October 29.

Van Kerkhoff, L., & Lebel, L. (2006). Linking knowledge and action for sustainable development. *Annual Review of Environmental Resources*, *31*, 445–477.

Walsh, C. J., Roy, A. H., Feminella, J. W., Cottingham, P. D., Groffman, P. M., & Morgan, R. P. (2005). The urban stream syndrome: current knowledge and the search for a cure. *Journal of the North American Benthological Society*, *24*, 706–723.

Wang, L., Lyons, J., Kanehl, P., & Bannerman, R. T. (2001). Impacts of urbanization on stream habitat and fish across multiple scales. *Environmental Management*, *28*, 255–266.

Xie, L., Rediske, R. R., Hong, Y., O'Keefe, J., Gillett, N. D., Dyble, J., & Steinman, A. D. (2012). The role of environmental parameters in the structure of phytoplankton assemblages and cyanobacteria toxins in two hypereutrophic lakes. *Hydrobiologia*, *691*, 255–268.

Zhang, X., Liu, X., Zhang, M., Dahlgren, R. A., & Eitzel, M. (2010). A review of vegetated buffers and a meta-analysis of their mitigation efficacy in reducing nonpoint source pollution. *Journal of Environmental Quality*, *39*, 76–84.